Origin of Earth's Water

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Santander June 18, 2012

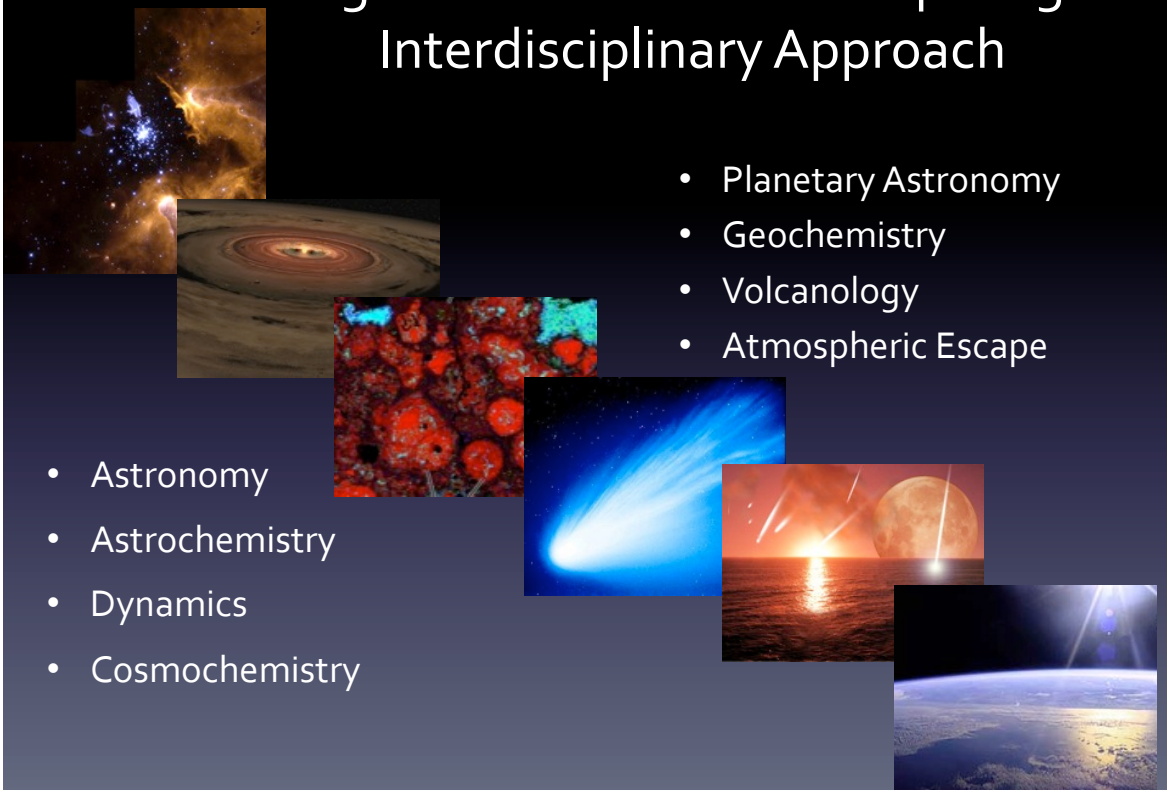
Our World is Special

Voyager 1 image of Earth, Feb. 14, 1990, from 6.4 billion km

Our planet is a lonely speck in the dark…The Earth is the only world known so far to harbor life - and this is likely because of water . . .

Carl Sagan, Pale Blue Dot, 1994, Random House

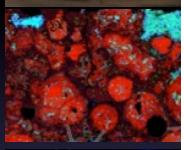
A Big Picture Question – Requiring An Interdisciplinary Approach

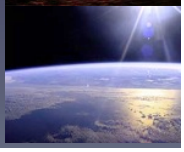


- Astronomy
- Astrochemistry
- Dynamics
- Cosmochemistry

- Planetary Astronomy
- Geochemistry
- Volcanology
- Atmospheric Escape

How the Ideas Developed





Bioastronomy 2004

- A post meeting field trip idea . . .

Important Considerations

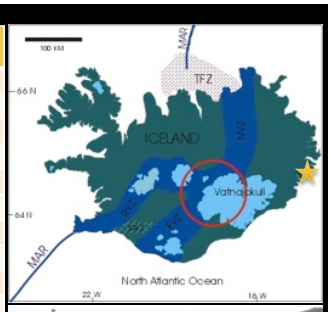
- What are issues related to the origin of Earth's water?
- Identify key unanswered questions
- What are the key chemical / dynamical clues?
- Identify areas where interdisciplinary research will help

Interdisciplinary Workshops

- Molokai Hawai'I – 2/27-3/1/08 – "Origin of Earth's Water I"
- Breiddalsvik, Iceland – 9/4-11/2011 – "Origin of Earth's Water II"

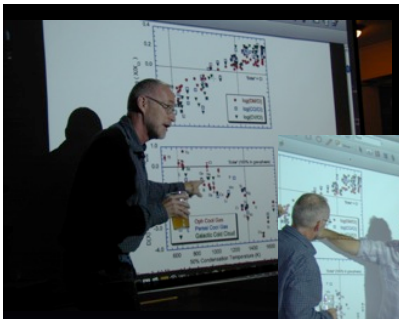
Last	First	Where	Field
Albarede	Francis	Univ. Lyon	Geochemistry
Cody	George	Carnegie	Organic chemistry, D/H fractionation
Drake	Mike	Univ. AZ	Geochemistry, gas adsorption
Elkins-Tanton	Lindy	MIT/Carnegie	Early Earth Atmosphere outgassing
Genda	Hidenori	Tokyo Inst. Tech	Magma ocean origin of water
Hirschmann	Marc	Univ. MN	Mantle oxidation, early atmosphere
Marty	Bernard	CNRS	Nobel gases, earth atmosphere
Mojzsis	Steve	Univ. CO	Geochemistry, early earth
Mottl	Mike	UH	Earth's water inventory
Pepin	Bob	Univ. MN	Geochemistry
Smyth	Joe	Univ. CO	Water in Earth's minerals
Stevenson	Dave	Caltech	Magma Oceans
Thordarson	Thorvaldur	U. Edinburgh	Volcanology, petrochemistry
Yokochi	Reika	Univ. Chicago	Early Earth outgassing

Last	First	Where	Field
Bergin	Ted	Univ. Mich	Protoplanetary disks
Dauphas	Nicolas	Univ. Chicago	Origin and evolution of volatiles
Desch	Steve	ASU	Early solar system– thermal models
Haghighipour	Nader	UH	Dynamics
Jewitt	Dave	UH/UCLA	Comets, KBOs, MBCs
Keane	Jacqueline	UH	Protoplanetary Disk ice chemistry
Keil	Klaus	UH	Cosmochemistry
Krot	Sasha	UH	Cosmochemistry
Levison	Hal	SwRI	Dynamics, SS formation
Meech	Karen	UH	Comets
Morbidelli	Alessandro	Nice	Dynamical models
Mottl	Mike	UH	Earth's water inventory
Mumma	Mike	Goddard	Comets
Owen	Tobias	UH	Isotopes, planetary atmospheres
Young	Ed	UCLA	Cosmochemistry



- Field Samples collected
- Outreach VFT filming
- Two papers in prep.
- New Science collaborations
- Water Origins III (Greenland)

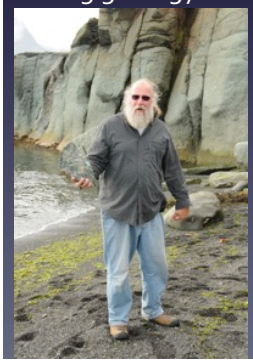
Workshop Discussions

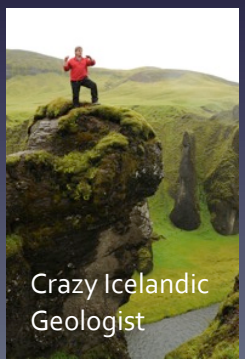


Late night sessions

Later night sessions

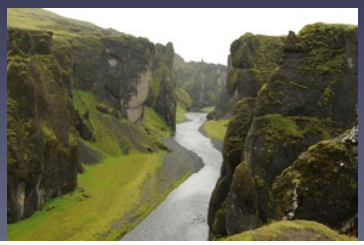
Planetary dynamicist doing geology . . .





Crazy Icelandic Geologist

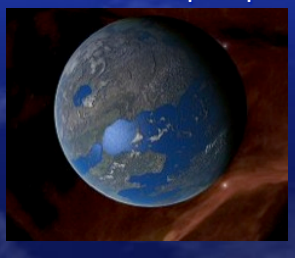
"This was the best day of my life"
"This was the most productive scientific workshop I've ever been to"

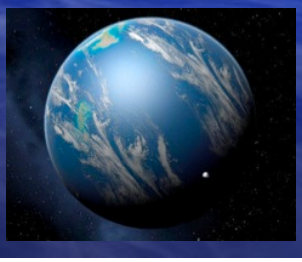


Big Picture Water Questions

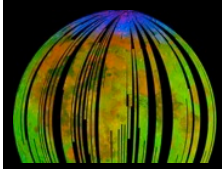
- Is the Earth relatively wet or dry?
- What is the threshold that matters for origin theories?
- How much do you change this number for Earth not to be Earth?
- What is the threshold for plate tectonics?

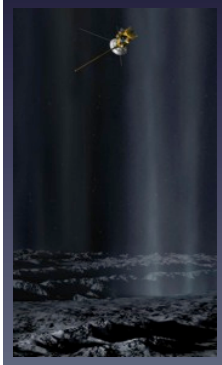
- As of June 18, 2012
  - 729 exoplanets confirmed around 580 stars
  - 2321 Kepler planet candidates



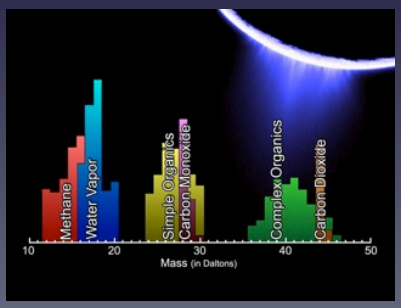


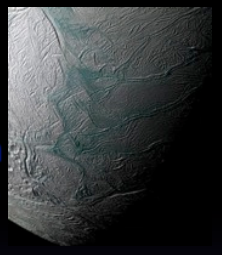
Water and NASA

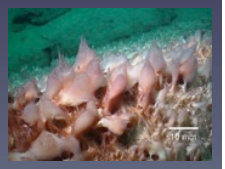




- Advance scientific knowledge of the origin and history of the solar system . . . and the potential for life elsewhere
- Water is key for habitability and Life
- Water is distributed throughout the solar system, yet …

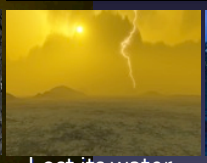






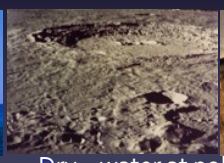
The Inner Planets are Dry . . .

Dry



Lost its water

Ocean 0.023%
Total ~ 0.05-0.1%

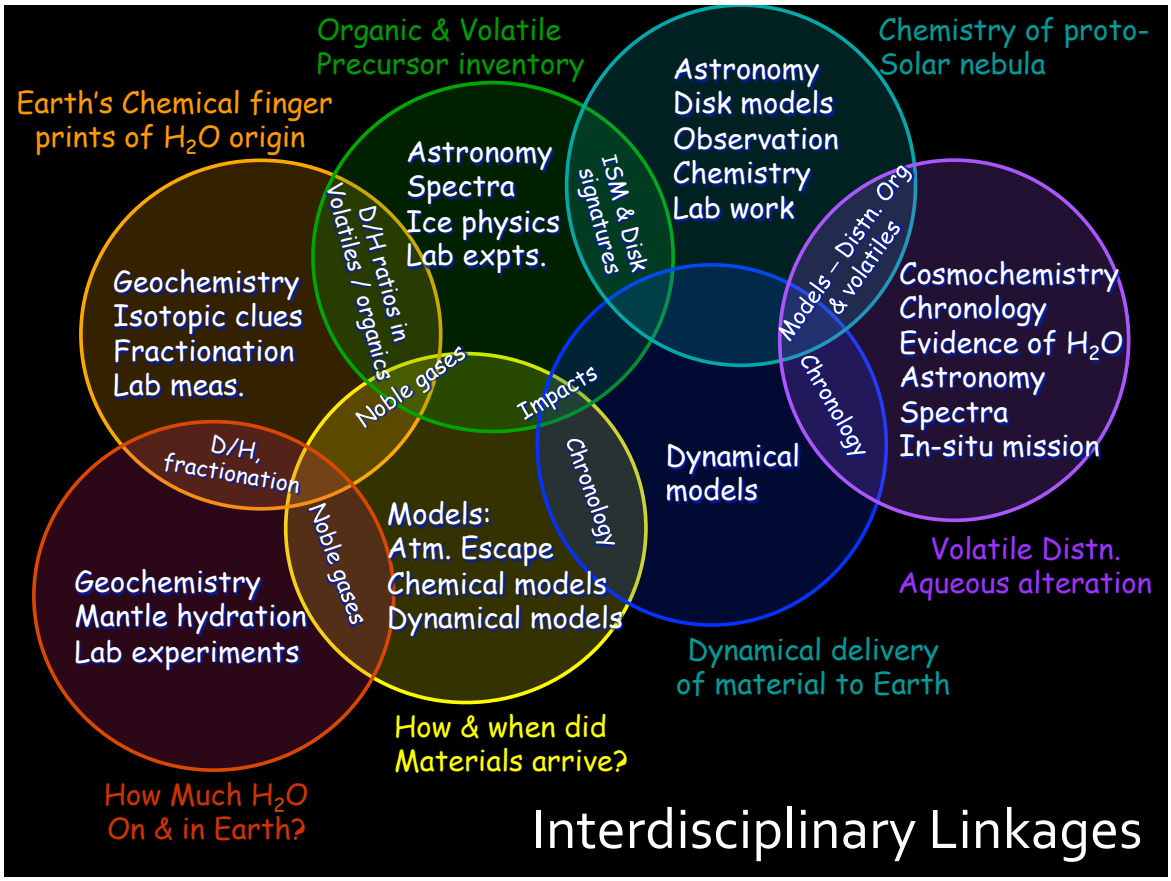


Dry – water at poles, subsurface

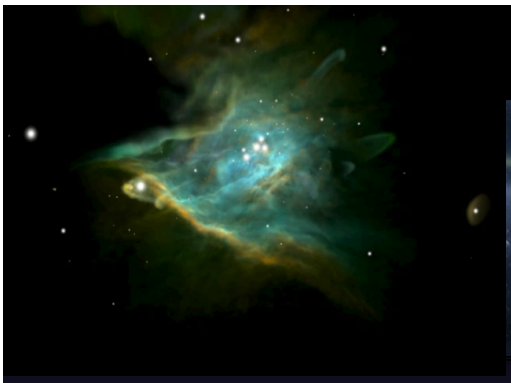
Almost Dry

Where and When?

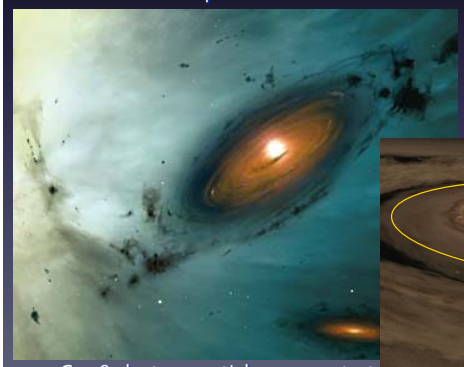
- How much water came from:
  - Hydrated planetesimals existing today (comets, asteroids)
  - Sources with no known current analogs
- Was Accretion uniform or sporadic?
- What happened to the water after it got here?
  - Is the Earth mostly degassed (dry)?
  - What is the form of water in/on Earth?
  - Can we study "primordial" water in/on Earth?



Collapse & Planetary Growth



1. Collapsing Gas cloud – Disk forms, Dust settles to mid plane

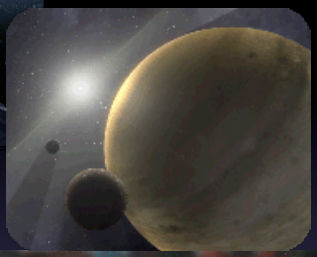


2. Gas & dust → particles concentrate due to turbulence → form planetesimals

The Snow Line

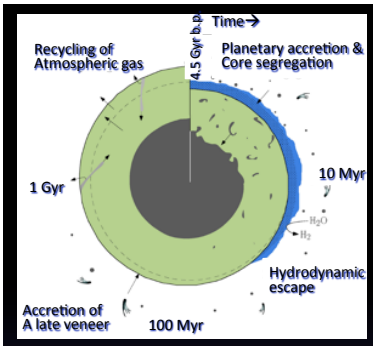
3. Oligarchic growth
4. Collisions & radial mixing

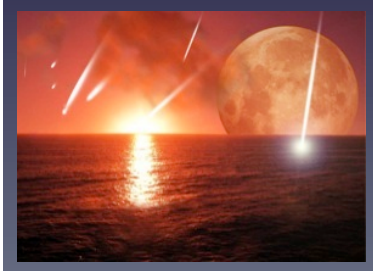
5. Gas accretion onto cores [Grand Tack model]



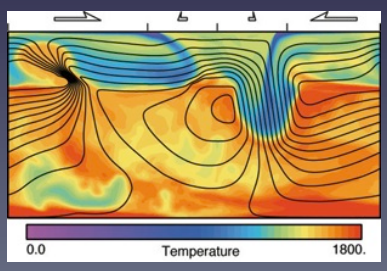
6. Instabilities, migration, collision & LHB [NICE model]

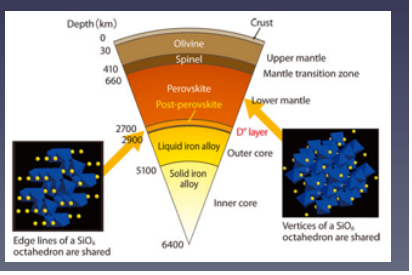
Early Earth Evolution



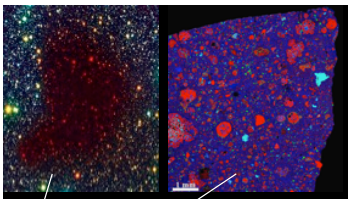


- Magma ocean solidifies (10^5-10^7 yrs)
  - Volatiles in: solids, liquids, primordial atmosphere
  - Cool dense material on top (unstable)
- Mantle overturn
  - Late additions may sink to core-mantle (D″)
    - Known from Seismic structure 200-300 km thick
    - Thermal/chemical boundary layer
    - Seismic speed changes → new crystal structure
      - Post-perskovite (Mg,Fe) SiO_3
    - 125 GPa, 2500K
- Heat radiates to space → cooling
  - Water in steam atmosphere condenses to ocean in 5-10 Myr





Origin of Earth's Water

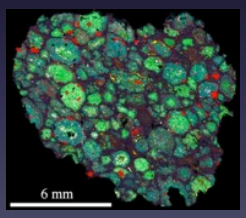


S. Mojzsis

By 4.3 Gyr: granites, rock cycle, Water veneer

t = 0 | 10 Million yr | 100 Million yr | 1 Billion yr

4.567 Gy – high temperature minerals, Cals



- Zircons ($ZrSiO_4$) back to 4.4 Gy
  - Stable to 1700C, don't easily dissolve in magma
  - Consistent w/solidification at low T (in water)

Origin of Earth's Water

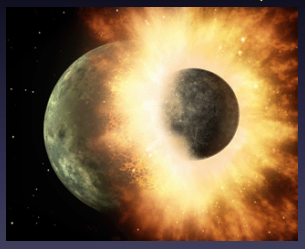
S. Mojzsis

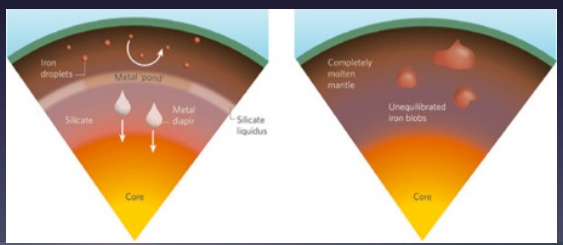
By 4.3 Gyr: granites, rock cycle, Water veneer

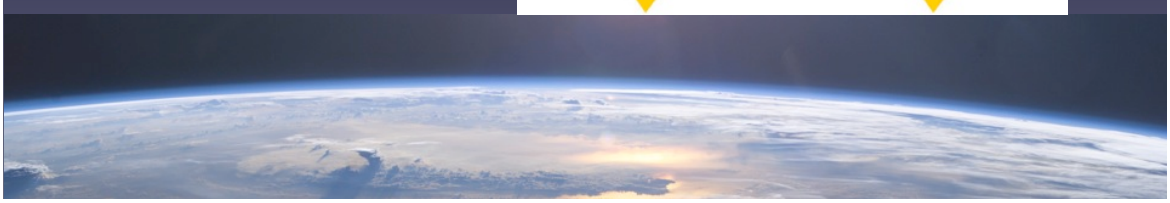
t = 0 | 10 Million yr | 100 Million yr | 1 Billion yr

4.567 Gy – high temperature minerals, Cals

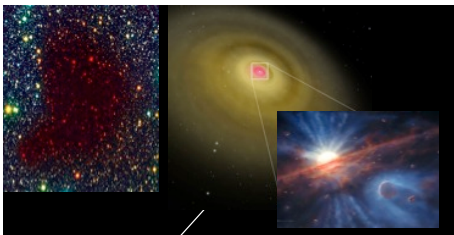
Moon forming event
Earth "formation"
Core "formation"







Origin of Earth's Water



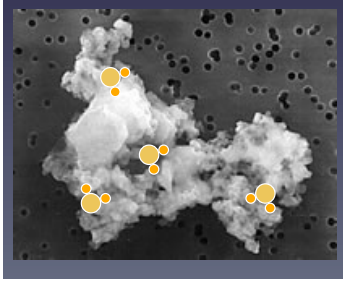
By 4.3 Gyr: granites, rock cycle, Water veneer

t = 0 | 10 Million yr | 100 Million yr | 1 Billion yr

4.567 Gy – high temperature minerals, Cals

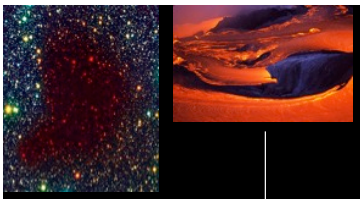
Moon, Earth & Core formation

- Capture from the nebula?
  - Gas sticking on dust (adsorption)
  - Does it survive the accretion process?



- Enough to bring ~ an ocean . . .?

Origin of Earth's Water



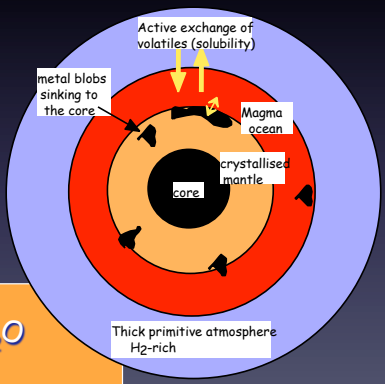
By 4.3 Gyr: granites, rock cycle, Water veneer

t = 0 | 10 Million yr | 100 Million yr | 1 Billion yr

4.567 Gy – high temperature minerals, Cals

Moon, Earth & Core formation

- Chemical reactions on Early Earth?
  - Multiple periods of magma oceans
  - Did nebular H_2 last long enough & coincide?

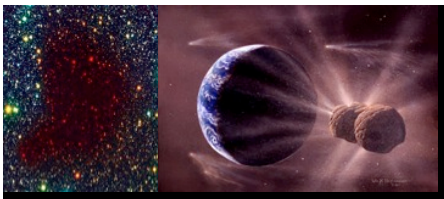


Atm H_2 + O → H_2O

O

Magma ocean oxides: FeO

Origin of Earth's Water



By 4.3 Gyr: granites, rock cycle, Water veneer

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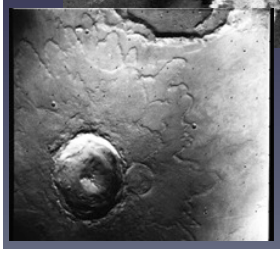
4.567 Gy – high temperature minerals, Cals

Moon, Earth & Core formation

- Brought in by distant icy planetary building blocks?



A Chemical Fingerprint

- A Theory from the 1980s
  - Comet delivery of water

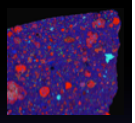
30x

12x

6.4x

3x

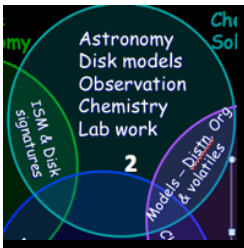
D/H



A few comets measured

Earth's Ocean

Solar system starting value

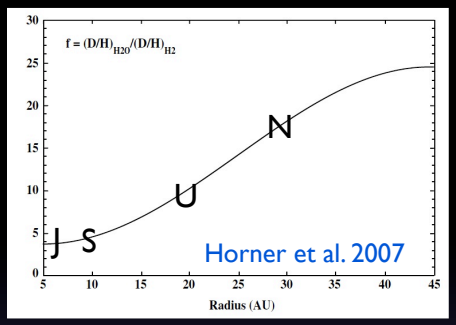


D/H Disk Gradients

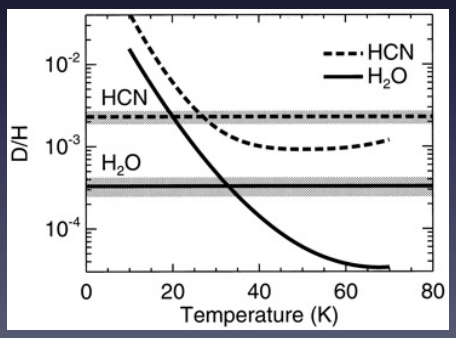
- Neutral exchange gas reactions predicts D enrichment in water (T dependent)

  $H_2O + HD \leftrightarrow HDO + H_2$

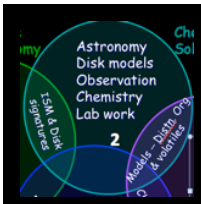
  - Hot water will have lower D/H, cold higher
  - Condensed ice preserves D/H from gas
- If water is interstellar
  - To alter the ratio need to evaporate and refreeze ice
- Predictions:
  - If all water originates in nebula: high D/H in outer nebula
  - Measurement of D/H in 2 species → ice formation nebular T



Model D/H enrichment in water as a function of disk Distance from star (e.g. Temperature).

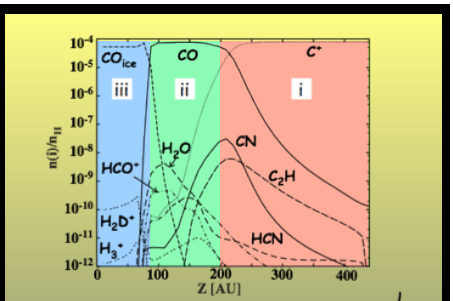


Model D/H in H_2O, HCN vs T in interstellar clouds, & measurements in Hale Bopp → ice formation T. (Meier, 1998)

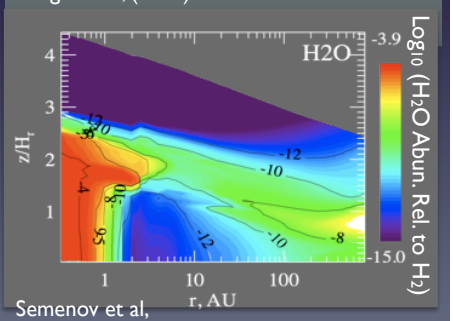


Disk Structure & Water

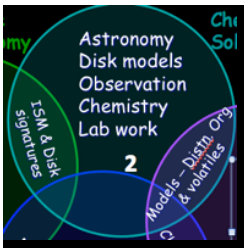
- Vertical Structure
  - I: High T, low density; II: Active chemistry, III: Freeze out
- Cloud Material Alteration
  - Accretion shocks: ice sublimation
  - Hot regions - water vapor abundant
  - Low T - Grain chemistry deuteration
- Snow line in TW Hya (Herschel + Spitzer)
  - Few AU
  - Hogerheijde, Bergin et al., *Science* (2011)



inside snow-line water evaporates off grains
Bergin et al, (2006)

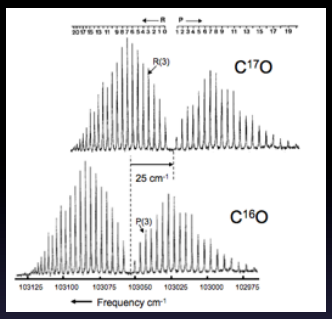


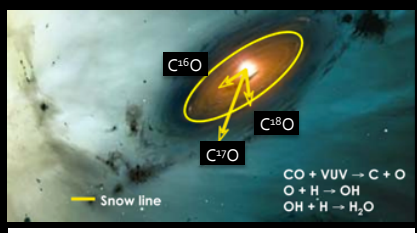
Semenov et al,

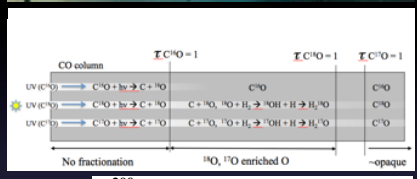


Protoplanetary Disk

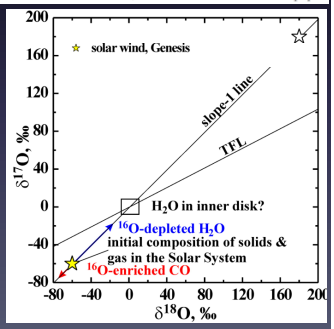
CO photodissociation
Far UV – 91.2-110 nm







- O isotopes give a clue about where water condensed
  - Oxygen has 3 stable isotopes: ^{16}O (99.763%), ^{18}O (0.199%), ^{17}O (0.037%)
  - Earth material plots with a slope 0.53 (TFL) (mass dependent fractionation)
  - Meteorites plot with slope 1: Mixing between 2 reservoirs gives slope 1 line
  - Fractionation due to absorption spectra of CO isotoplogues not overlapping
- Prediction:
  - CO self shielding can imprint isotopic signature to water
  - Things forming in the inner disk should have $^{17,18}O$-rich water



Insights from the Disk: The Snow Line

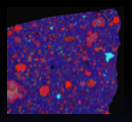
- Water was present at all stages of disk (ice, gas, liquid)
- Heavy chemical processing in disk: D/H Fractionation
  - With strong radial and vertical gradients
  - Expect comets / icy bodies forming at different r to have different D/H
  - Oxygen isotopes may help tell us where water forms
- Debate over the location of the "snow line"
  - Disk models can have it as close as 1-2 AU
  - Dynamics and growth of Jupiter: near 5 AU in our solar nebula
  - The snow line moves in time
  - Spitzer + Herschel – snow line in 1 system @ a few AU

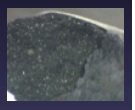
A Chemical Fingerprint

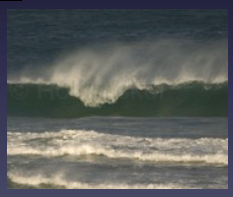
30x

12x

A few comets measured





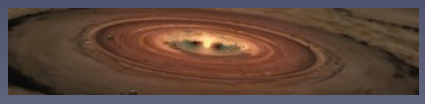


Earth's Ocean

6.4x

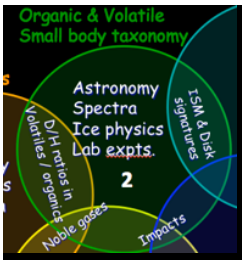
3x

Solar system starting value

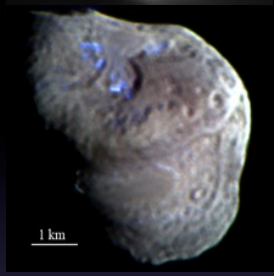


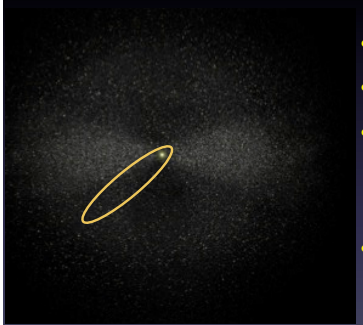
?

D/H

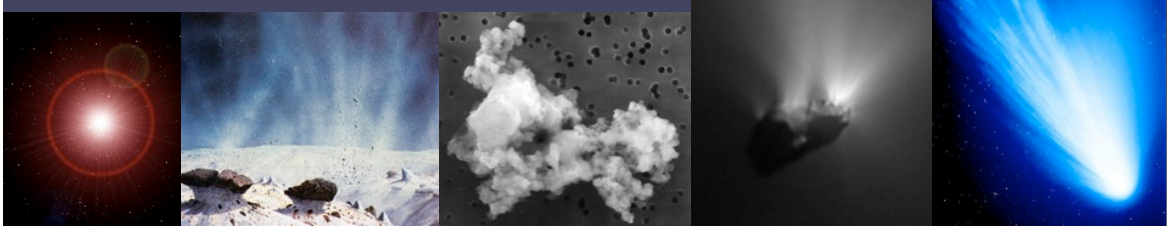


Primitive Bodies & Early Solar System





- Comets: remnant km-scale icy planetesimals
- Formed outside the snow line
- Perturbations bring them close to the sun
  - Sun's heat causes sublimation
  - Drags dust off and we measure dust and gas
- Goal: use chemistry to understand formation location

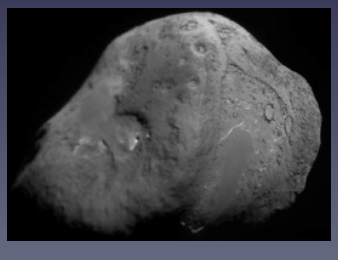


How Many Comets?

Ocean 0.023% = 1.37×10^{21} kg

Total ~ 0.05-0.1% = $(2.9\text{-}59) \times 10^{21}$ kg

Icy Reservoir	Mass [kg]	# Needed to supply Earth's Ocean
Comet Tempel 1	~ 8×10^{13} kg	20 million
Comet Hale Bopp (40 km radius)	~1.3×10^{17} kg	~10,000
Sungrazing comets	Few x 10^{18} kg	< 100 for Earth's water

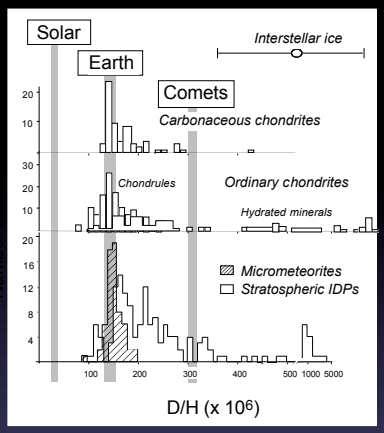


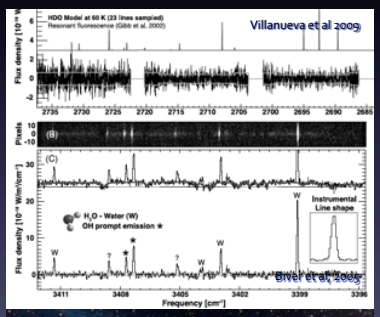
A'Hearn et al. Deep Impact)

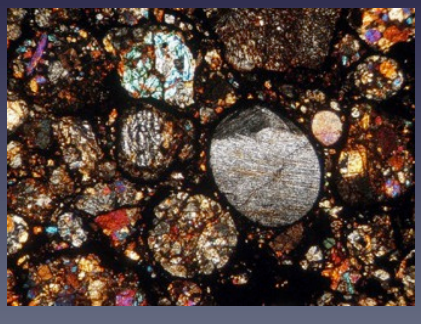
A. Gomez (CTIO)

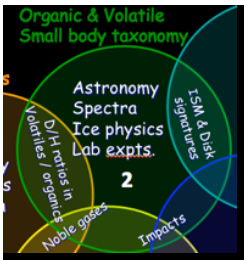
Farnham & Schleicher

Comet & Asteroid Measurements

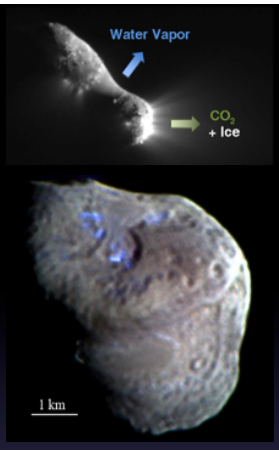




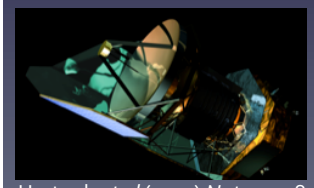




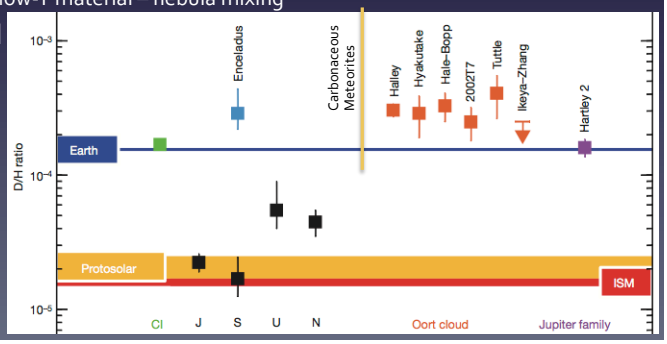
Primitive Bodies & Early Solar System

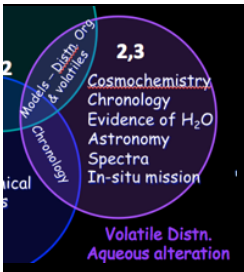


- Isotope stories – Not yet clear (too little data)
  - D/H in most comets measured is ~ 2 x SMOW
- Heterogeneity in chemistry – uncorrelated with dynamical class
  - Within individuals and across classes of comets
  - Groupings for volatile organics: depleted, normal and enriched
  - Some comets enriched in CO_2
- Paradigms are changing about formation location & dynamical delivery
  - Stardust – comets are a mix of high-T and low-T material – nebula mixing
- Origin-Evolution not well understood

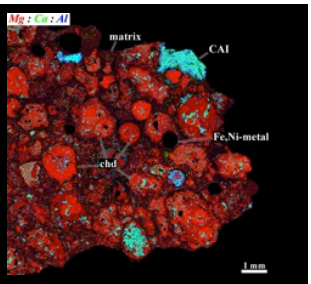


Hartogh *et al* (2011) *Nature* 478

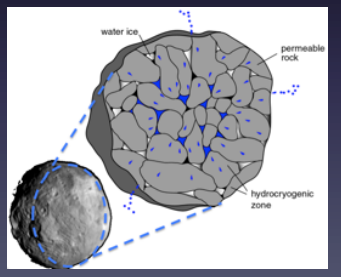




Meteorites & Water: Aqueous Alteration



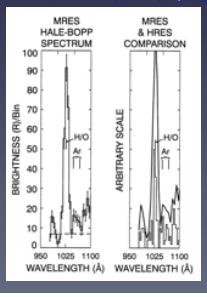
- Chondrite parent bodies accreted over several Myr
  - They accreted as water ice & dust and were then heated (form outside snow line)
  - The amount of aqueous alteration can't be from gas adsorption → icy grains + hydrothermal
- Classification based on composition & alteration amount
  - Only have samples from 15 groups
  - Water content ranges from a few wt% to 20 wt% water
  - Alteration occurred at low to high temperatures (300-1200K)
- Accretion places of CCs & origin of water in these unclear
  - Aqueous alteration seen everywhere
  - Probably formed in main asteroid belt
  - Parent bodies probably formed in different disk locations
  - D/H isotope fractionation is possible during aqueous alteration
  - D/H better matches Earth oceans

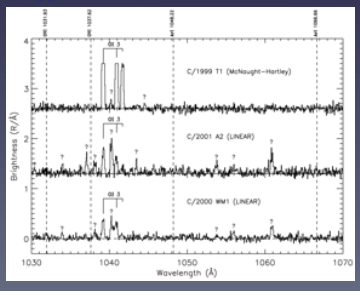


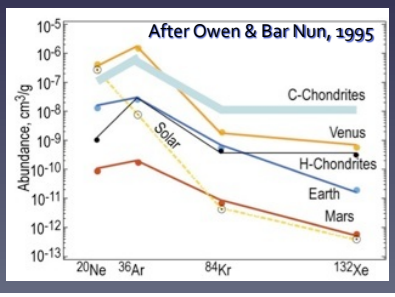
The Noble Gas Problem

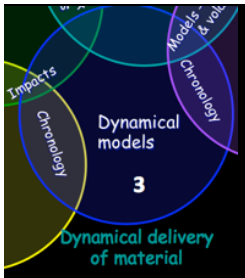
- Meteorites don't only bring in water . . .
- Noble gas patterns
  - CCs, contain 20x more Xe relative to Kr than on Earth or Mars
  - If noble gas trend for embryos resemble those in CCs, (increasing w/ *r*)
    - Little embryo material was needed to make Earth
    - The noble gases brought will not match the Earth
  - Argues against embryo (asteroid) delivery of Earth's water
- No detection of noble gases in comets – only limits
  - Low T ice experiments suggest abundances should match Earth & Mars
  - Requires far UV (sounding rockets, UV satellites)

Stern et al. (2000) ApJ 544, L169;
Weaver et al. (2002) ApJ 576, L95

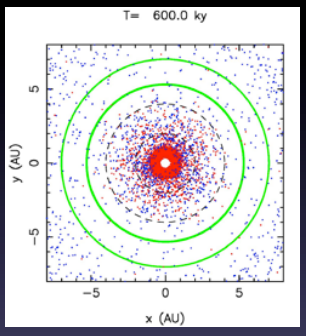






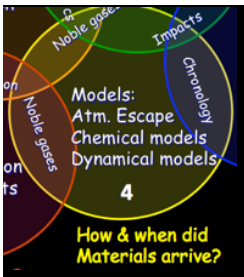


Early Solar System Dynamics – Evolving

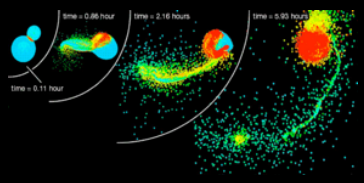


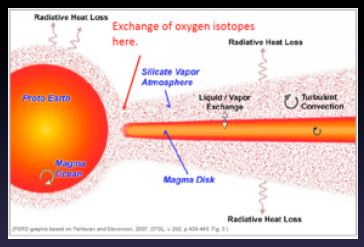
- Morbidelli *et al* 2000 – dynamics post-Jupiter form
  - Earth accreted inside snow line – Water came later after Earth formed
  - Amount of comets delivered to Earth < 1/50 of an ocean
  - Dynamically easier to bring water from asteroid embryos
- Grand Tack (Walsh *et al*, 2011)
  - Explains low mass of asteroid belt & can make Mars
  - Delivers icy objects from outer solar system to Earth
- Planetesimal Migration Model (Minton & Levison 2011)
- Implications for water delivery?
  - Delivery of icy objects from everywhere?
  - Do D/H gradients in the disk matter?

"I used to think the dynamicists had almost solved everything . . . . But now, well, it is a mess . . . ."
(anonymous prominent planetary astronomer)



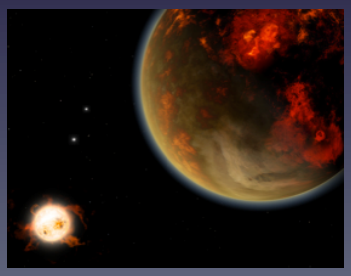
Losses: Impacts Deliver & Remove





Desch & Taylor, 2011

- Moon as a test bed – clues to original inventory?
  - Giant Impact formation models: Rapid loss from disk atmosphere, but not from magma
  - Lunar Rocks: Water content of moon from lunar rocks (Hauri '09)
- Magma Oceans – Why do we care?
  - Storage and fractionation of volatiles
  - Differentiation & Core formation and timescales



A Chemical Fingerprint

30x ?

12x

A few comets measured

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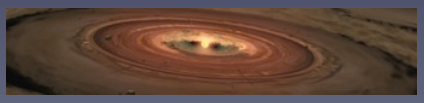
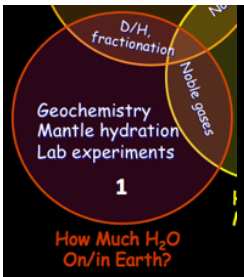
Earth's Ocean

3x

Solar system starting value

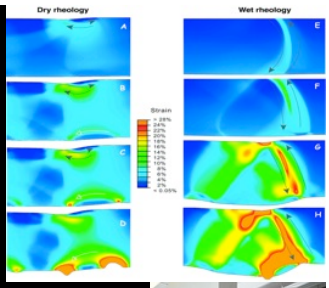


D/H ?

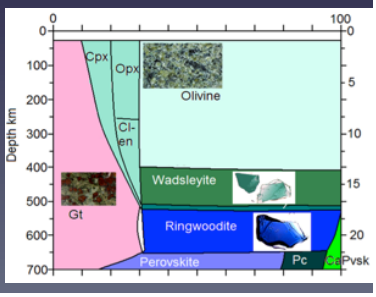


How Much Water?

Ragenauer-Lieb, *Science*



- How do we know there is water in Earth? Affect how earth operates?
  - Water in Earth: stored as OH in nominally anhydrous minerals
  - Do we see evidence of deep water cycle ?
    - Water effects: elasticity, phase transition, melting, electrical conduction, viscosity
    - Water essential for Plate Tectonics
- If earth accreted wet didn't completely degas → interior would be wet
  - Hard to fit velocities in transition zone with anhydrous minerals
- Where is the water? [Observation & Experiments]
  - Lithosphere – less water with depth
  - Upper mantle – water storage ability increases w/depth
  - Transition zone – vast capacity (> 10 oceans), likely 1.5-3 oceans
  - Lower mantle – limited – but may depend on phase D" layer
  - Could have up to 50 oceans
  - Core is a wildcard

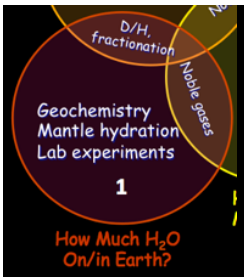


How Much Water?

In units of Ocean volumes

Region	Low	High	Capacity
Ocean/Atm	1.32	1.32	1.32
Crust	0.02	0.10	0.1
Lithosphere	0.04	0.49	3.3
Mantle	0.04	4.2	15.1
Core	0.03	2.8	28.1
TOTALS	1.5	11.2	59.7

Mottl, Glazer, Kaiser & Meech (2007), ChEG 67, 253.

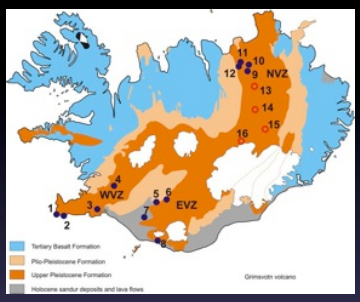


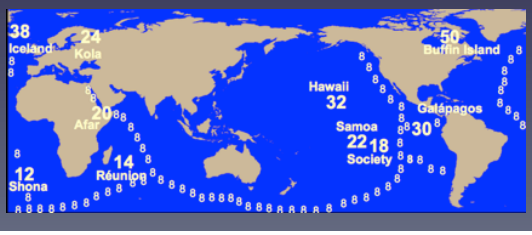
How Much Water?

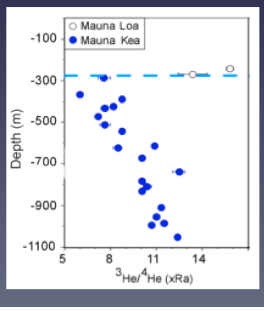
- Knowledge of amount water on present Earth very uncertain
  - Don't know amount of Earth's water in crust / mantle to > 2x
  - The deeper we go, the more uncertain the estimates
  - The core is a wild card (but not relevant?)
- There may have been a larger inventory in the past
  - What were the loss processes, when and how much?
- Water is key to not only life but habitability
  - Is the interior water different isotopically?
  - Can we access it?

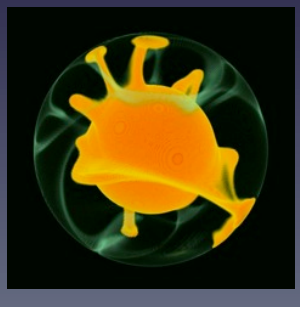
Can we Measure Water from Earth's Interior?

- Does Earth still have primitive volatiles?
  - The $^3He/^4He$ ratio – an interstellar signature
  - $^3He/^4He$ increases in Earth
- Is there accessible primitive water?
  - Mantle plumes (Hot spots) bring material from depth
  - Some materials survive transport
  - Rocks from depth: high $^3He/^4He$ → primitive
  - Hawaii & Iceland

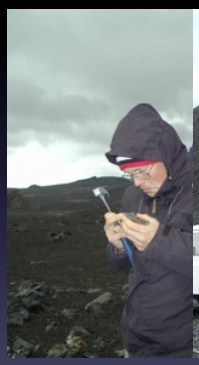


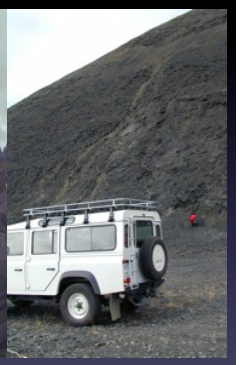




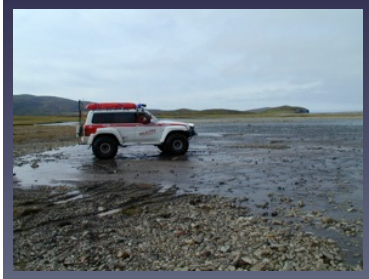


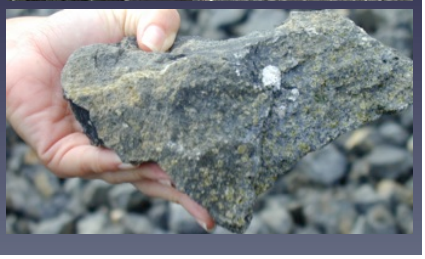
Iceland Sampling





- Why are we sampling along the MOR in young lavas to get the oldest (primordial) material?
- How do we sample?





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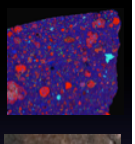
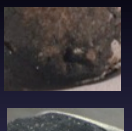
12x

A few comets measured





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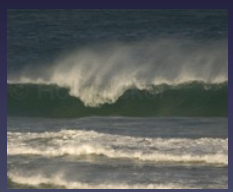
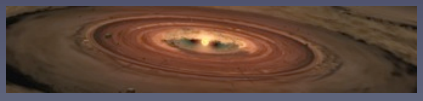


Earth's Ocean

6.4x

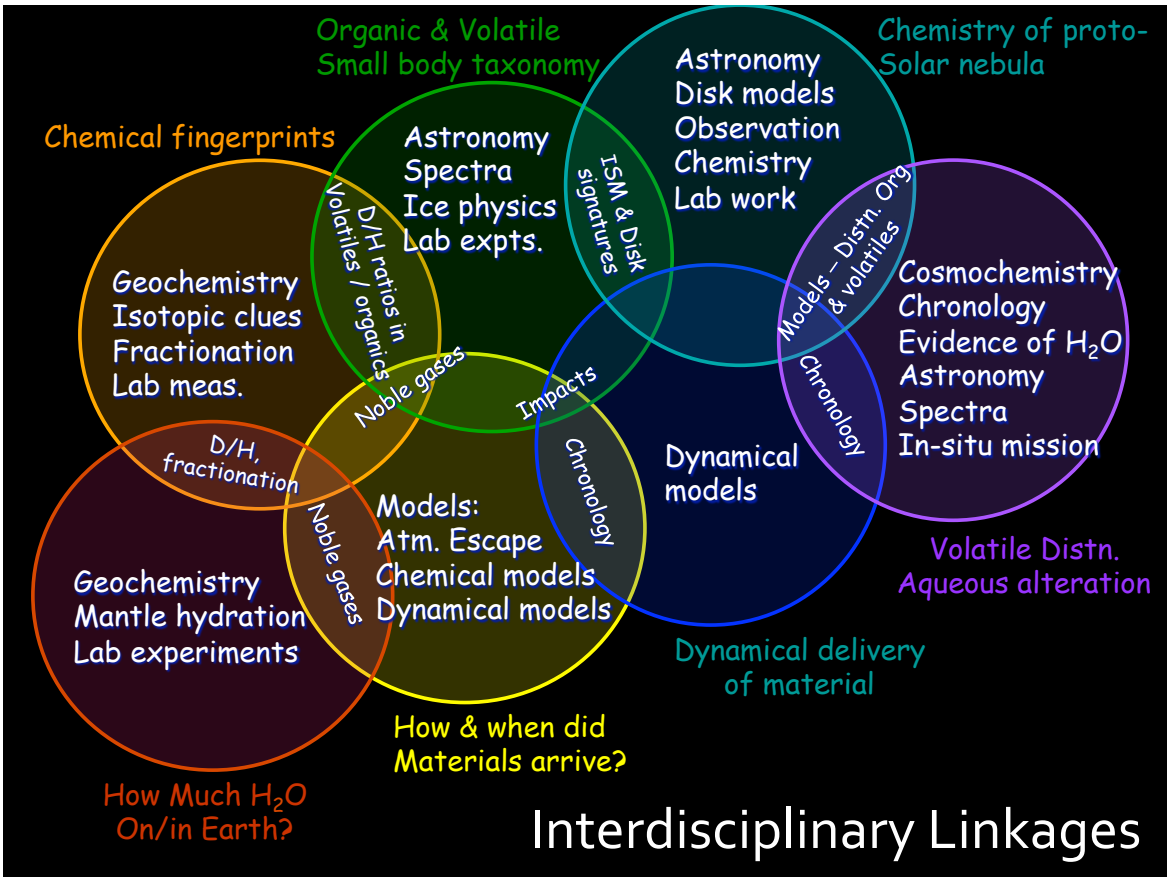
3x

Solar system starting value



?

D/H



What do we Think we Know?

- Know of several reservoirs of D/H in solar system
- Comets are chemically divided into classes
- Samples from about 15 asteroid parent bodies – water everywhere

- Getting a better understanding of disk chemical models
- Better understanding of how to make a planetary system (we think . . . .)

- Unmistakable signature of He and Ne from the solar nebula in Earth's interior – so why not water?
- Earth suffered massive volatile loss many times

Key Measurements Needed

- D/H gradients in disks to verify chemical models (ALMA)
- Huge lack of data on comets
  - Need better statistics – few comets measured
  - Noble gases based on lab experiments → space missions
- Need to know bulk Earth D/H
  - Are we accessing primordial water: need more samples / analyses
- Need to understand fractionation processes in Earth
  - Modeling atmospheric escape, impact delivery

Some Take Away Numbers

Earth's Water Content

- ?? % comets
- ?? % hydrated asteroids
- ?? % solar nebula gases
- ?? % chemical reactions on Earth

Perhaps the journey is more important than the destination . . .

Water probably came from many sources – it is a matter of how much, when and from where

"So, we spent 2.5 days deciding we don't know anything . . . ." – Mike Drake (2008)

"Exciting developments in several areas are leading to insight that will help us address the Origin of Water" – various (2011)